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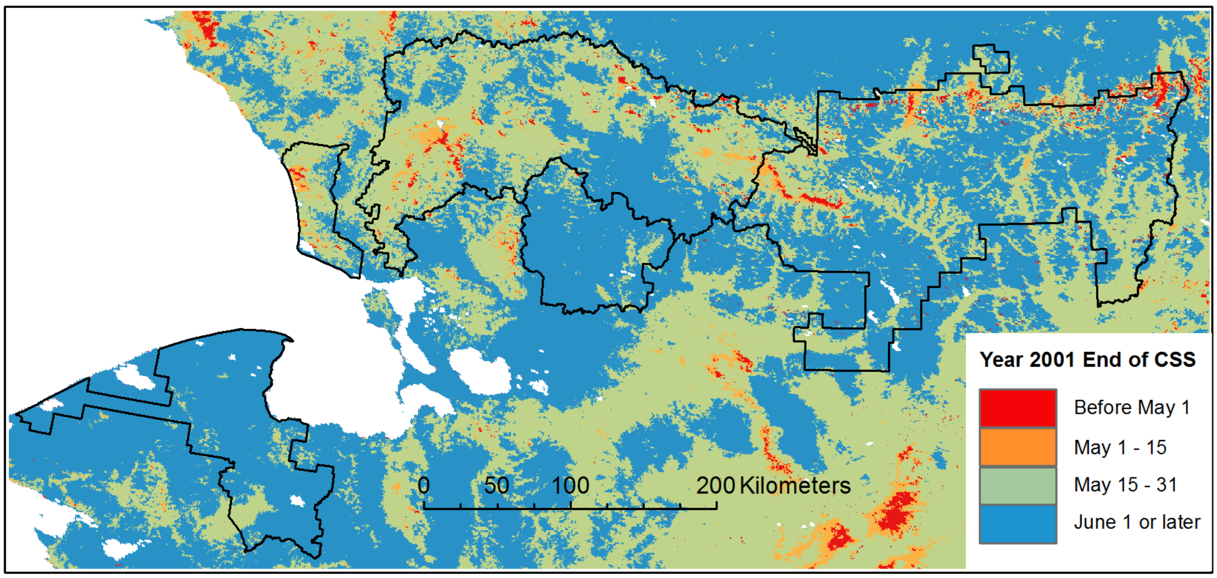
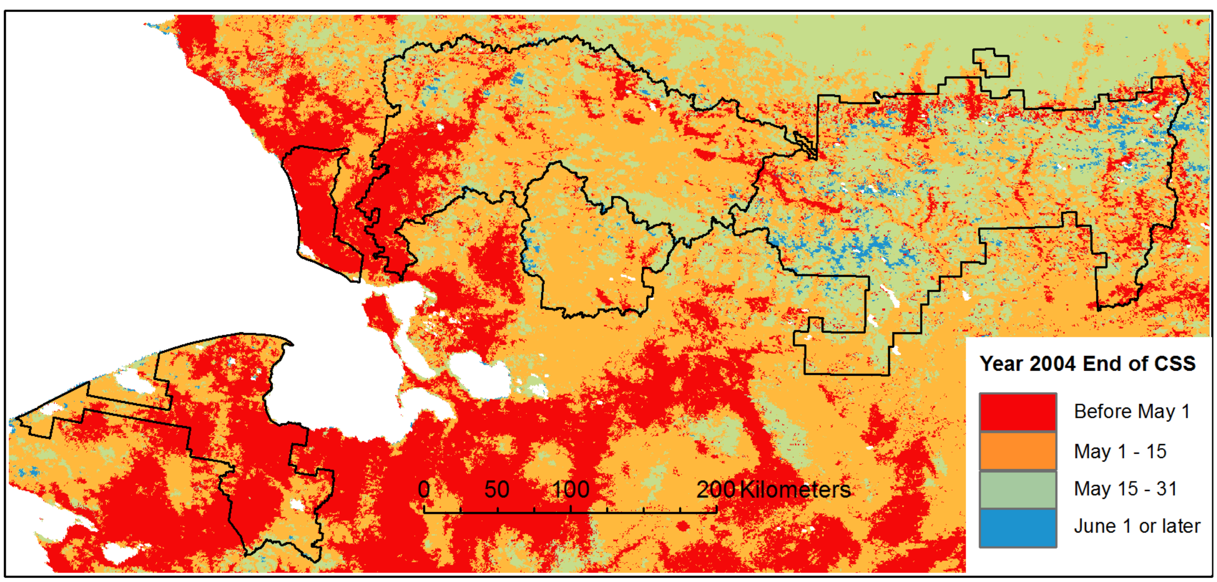
Natural Resource Stewardship and Science

Snow Cover Monitoring with MODIS Satellite Data in the Arctic Inventory and Monitoring Network, Alaska, 2000-2013

Natural Resource Data Series NPS/ARCN/NRDS—2014/634





ON THE COVER
Date of the end of the continuous snow season (CSS) in in the NPS Arctic Inventory and Monitoring Network in a year with late snow cover persistence (2001) and early snow cover loss (2004), derived from MODIS satellite imagery.

Snow Cover Monitoring with MODIS Satellite Data in the Arctic Inventory and Monitoring Network, Alaska, 2000-2013

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Fort Collins, Colorado

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Abstract

Snow cover was monitored in the five National Park Service (NPS) units of the Arctic Inventory and Monitoring Network (ARCN) from the fall of 2000 through the spring of 2013, using 500 m resolution daily data from the MODIS Terra satellite. The MODIS data were processed by the National Snow and Ice Data Center (NSIDC) and the Geographic Information Network for Alaska (GINA) at the University of Alaska Fairbanks to detect the first and last snow days of each season, and the start and end of the continuous snow season (CSS).

The median first snow day was in October over most of the low-elevation areas (<2000 feet, 620 m) of ARCN and mainly in September at higher elevations, except at elevations above 3000 feet (914 m) along the north side of the Brooks Range, where the first snow came in August. The start of the CSS was within 2 weeks of the first snow day over most of ARCN: late October in the lowlands (<1000 feet, 305 m) of western ARCN and early October elsewhere, except at elevations above 3000 feet (914 m), where the CSS began in September. In years with late snow cover establishment and cloudy fall weather, the date of first snow and the start of the CSS were not detected in some parts of ARCN before winter darkness and long terrain shadows obscured the ground. While this problem appears to not have substantially affected the long-term median values for first snow day and start of CSS, it prevented analysis of year-to-year variability in these two metrics.

The median length of the continuous snow season was 6 to 7 months in most lowland areas (below 1000 feet, 305 m), 7 to 8 months at most mid-elevations, and 8 to 9 months at most high elevations (above 4000 feet, 1219 m). The median last snow day and median last day of the CSS were less than a week apart in May over most of ARCN. Higher elevations in ARCN generally had later snow-off dates, though there was some interesting variability within this overall pattern. Snow usually disappeared in April and early May in valleys on the north side of the Brooks Range in Gates of the Arctic National Park and Preserve, in parts of the Noatak Valley, and on the hills that face the Chukchi Sea in Cape Krusenstern National Monument. These anomalous early snow-off areas probably had thin snow covers as a result of both high winds and relatively low snow precipitation.

Over most of ARCN the standard deviation in end of CSS was 14 days or less, which means that the snow disappeared within the same 1-month period in about 2 out of 3 years. Variability was greatest on slopes along the northern edge of the Brooks Range. The years with the most extreme deviation in end of CSS were 2001 (late snow persistence) and 2004 (early snow cover loss). Linear regression of end of CSS vs. year and last snow day vs. year for individual pixels showed no significant trend over the period 2001-2013 in our study area.

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Acknowledgments

The development of MODIS snow metrics was primarily the work of Jiang Zhu of the Geographic Information Network for Alaska (GINA) at the University of Alaska Fairbanks, with the collaboration of many others, including Chuck Lindsay, Amy Miller, and Parker Martyn of the NPS; Tom Heinrichs, Dayne Broderson, Jay Cable, and Will Fisher at UAF GINA; and Michael Budde of the U.S. Geological Survey. Ken Hill, Jim Lawler, and Amy Miller of NPS provided helpful review comments for this manuscript.

Introduction

Snow dominates the arctic environment. It covers most of the landscape for well over half of the year, and all the organisms that live in the arctic beyond the short summer must be adapted to deal with snow and cold. The snow cover in the arctic persists continuously through the long winter, and it disappears quickly in the spring, generating a major runoff event (Kane et al. 2000, Olsson et al. 2003)

Most of the snow cover in ARCN is the tundra type in the classification scheme of Sturm et al. (1995): the snowpack is thin, cold (below -10° C for most of the winter), and windblown, consisting of a basal layer of depth hoar overlain by multiple wind slabs. The tundra snow cover is unevenly distributed across the landscape due to wind (Benson and Sturm 1993). Where windblown snow accumulates, the snow cover is the less common “deep tundra” type (>75 cm deep). A taiga snow cover class is probably present in some of the forested areas of southern GAAR and KOVA. The taiga snow type is less dense because it is not windpacked, and it consists mostly of depth hoar with a surface layer of loose, new (un-metamorphosed) snow.

Over the past century the spring snow cover area across North America has become smaller in concert with rising temperatures (Brown and Robinson 2011). A reduction in the length of the snow season has been in observed in Alaskan arctic since 1940 at Barrow (Hinzman et al. 2005). A change in snow cover duration in ARCN would have widespread ecological implications, influencing the land surface energy budget, the hydrologic cycle, access by wildlife to forage and protection of subnivian wildlife from weather and predators (Eastland et al. 1989, Euskirchen et al. 2007, Callaghan et al. 2011, Tape et al. 2010). Shrubs have been increasing in the arctic over recent decades, and snow depth has a positive feedback relationship with shrub cover in the arctic (Sturm et al. 2005, Tape et al. 2006).

The great importance of snow in the arctic environment has led NPS to include snow cover monitoring as a part of its Terrestrial Landscape Patterns and Dynamics vital sign (Lawler et al. 2009). This monitoring program includes snow cover monitoring of the entire ARCN area by satellite, as well as on-the-ground observations of snow cover with remote automated cameras that are integrated with climate monitoring stations. The MODIS (Moderate Resolution Imaging Spectroradiometer) Terra satellite has been gathering data daily since the year 2000 that can be analyzed to determine the extent of snow cover in ARCN. The purpose of the present report is to summarize the snow cover data available to date for ARCN from this satellite.

Methods

Study Area

The Arctic Inventory and Monitoring Network (ARCN) includes the 5 National Parks Service (NPS) units in northern and northwestern Alaska (Fig. 1). This region contains large expanses of rugged mountains, with elevations up to about 8500 feet (2600 m) in GAAR (see Fig. 1 for NPS unit abbreviations). Extensive lowland plains cover parts of NOAT and KOVA and much of BELA. Vegetation is mostly arctic tundra, with boreal forest present in the southern lowland areas of GAAR and KOVA, and small parts of CAKR and NOAT

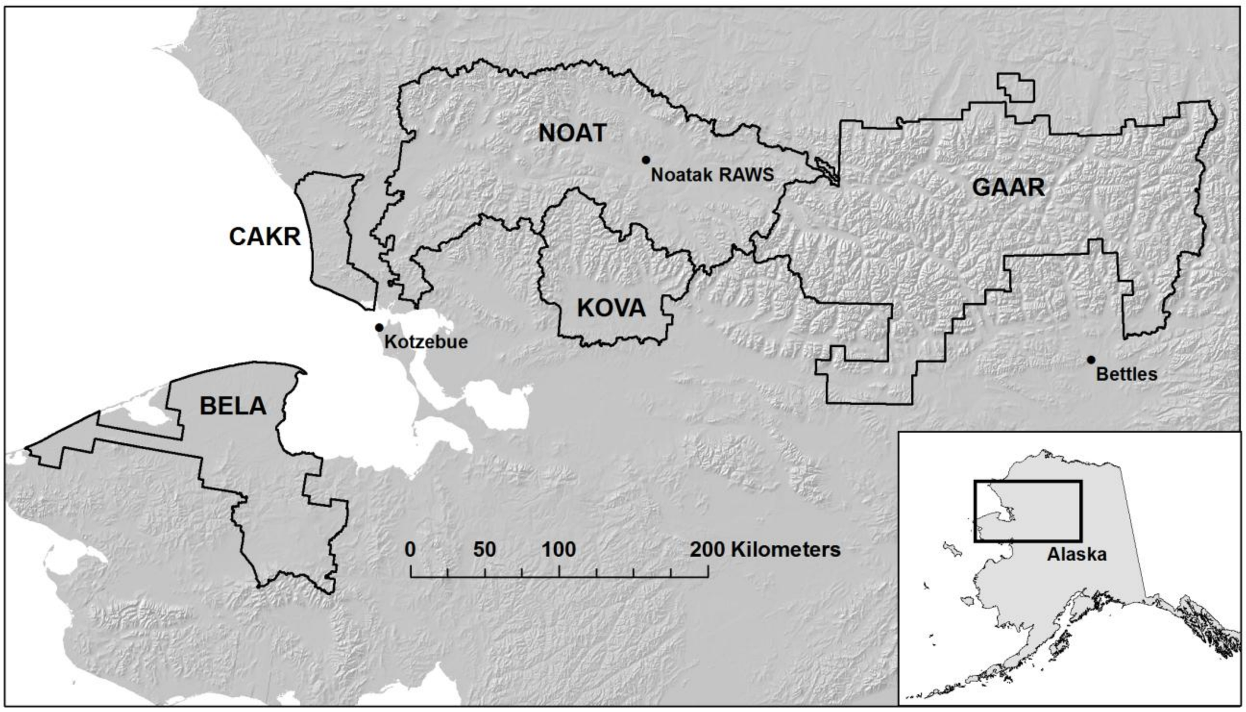

Figure 1. The NPS Arctic Inventory and Monitoring Network (ARCN). The NPS units in ARCN are the Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and the Noatak National Preserve (NOAT).

Long-term average temperatures are available for Kotzebue (representative of coastal lowland areas of western ARCN; see Fig. 1 for station locations) and the Noatak RAWS (at 985 feet or 300 m elevation, representative of low-elevation inland areas; Fig. 2). Inland areas warm more quickly in the spring, cool off sooner in the fall, and have lower winter temperatures. Daily average air temperatures at both stations rise above freezing in mid-May and drop below freezing in mid-September (Noatak RAWS) to near October first (Kotzebue; Fig. 2). We currently lack long-term data from higher elevations, but presumably below-freezing daily average temperatures typically arrive there later in the spring (e.g., late May) and earlier in the fall (e.g., early September). For future analysis we will be able to use the sixteen new climate monitoring stations that were installed in 2011-2013 in ARCN by NPS, including five between 3,100 feet (954 m) and 4360 feet (1329 m. (see http://www.raws.dri.edu/wraws/akF.html).

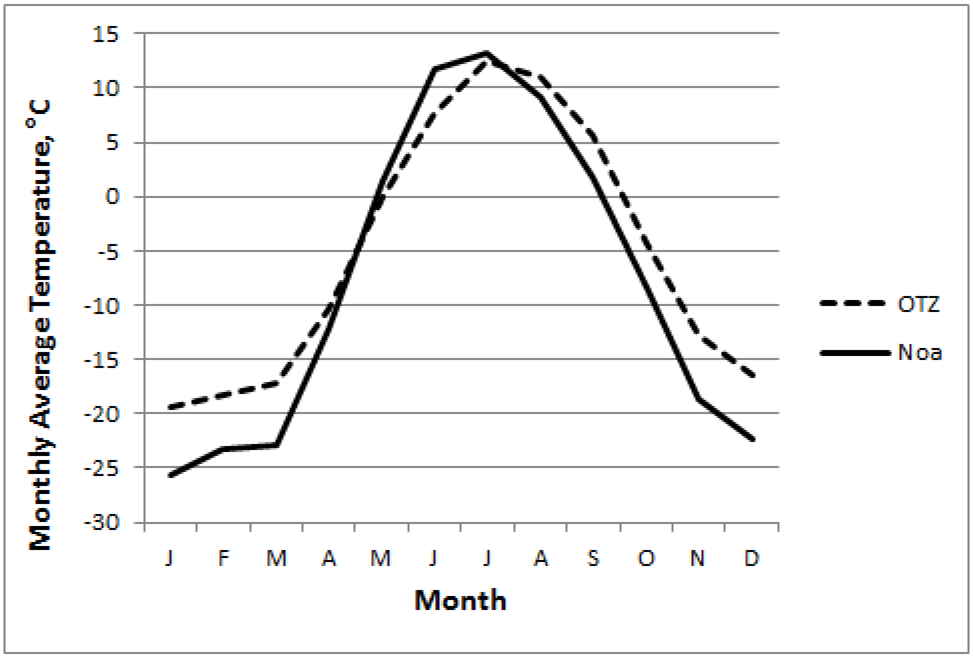

Figure 2. Monthly average temperatures at Kotzebue (OTZ) and the Noatak RAWS (Noa). Kotzebue is near sea level on the Chukchi Sea coast (Fig. 1; National Weather Service data, climate normals for 1980-2010) and the Noatak RAWS (NPS data for 1990-2013 from http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?akANOA) is in the central Noatak Basin in NOAT at an elevation of 985 feet (300 m; Fig. 1).

Modeled estimates of mean precipitation during the months with below-freezing average temperatures in ARCN (i.e. months when precipitation falls as snow, October through April) show amounts ranging from near 100 mm in the Itkillik River valley of far northeastern GAAR to just over 300 mm in the mountains of southern BELA and southwestern GAAR (PRISM 2009; Fig. 3). There are currently no multi-year, year-round precipitation records for ARCN.

Image Analysis

The MODIS Terra Snow Cover Daily L3 Global 500m Grid data (MOD10A1; NASA 2013) from the National Snow and Ice Data center (NSIDC: http://nsidc.org/data/modis/) were used to determine the snow season. The MODIS Terra satellite gathers multispectral data daily at 10:30 AM local time. Data were available from this satellite from the fall of 2000 through the spring of 2013 at the time of writing. Each pixel was screened for clouds by NSDIC using the MODIS cloud mask product MOD35_L2 (http://modis-atmos.gsfc.nasa.gov/MOD35_L2/index.html; Ackerman et al. 2010). In cloud-free pixels, snow cover (snow present or not present), snow albedo (the percentage of solar radiation reflected), and fractional snow cover (estimated snow cover in percent) were mapped by the NSIDC using a snow mapping algorithm based on the Normalized Difference Snow Index (NDSI) and other criteria (Hall et al. 2006, Riggs et al. 2006). The snow cover (presence/absence) value was derived from threshold tests applied to the NDSI and other satellite measurements, while the fractional (percent) snow cover value was computed using the regression relationship with NDSI developed by Salomonson and Appel (2004).

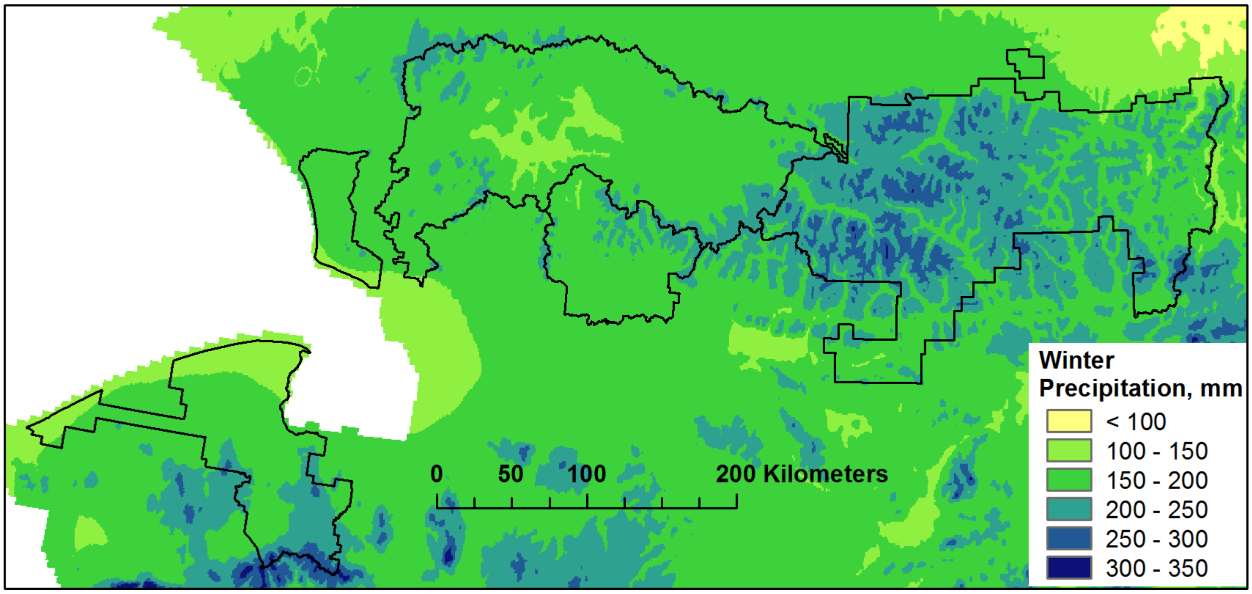

Figure 3. Total average winter (October-April) precipitation in ARCN, modeled for the period 1971-2000 by the PRISM Climate Group (2009).

Determination of the start and end of the snow season is complicated by clouds and by the fact the snow cover in a season may be interrupted by snow-free periods. Additional processing of the daily NSIDC snow product, to interpolate across cloudy periods and detect the start and end of snow cover periods of different lengths, was performed by the Geographic Information Network of Alaska (GINA) at the University of Alaska, Fairbanks (see http://www.gina.alaska.edu/projects/modis-derived-snow-metrics). The GINA snow metrics algorithm involved repeated passes through the daily time-series data for each pixel, forward and backward in time within each snow year. (A snow year was defined as August 1 to July 31). Pixels were classified as "snow covered" if they had >50% fractional snow cover and albedo >30% on the NSIDC raster. First, a spatial filter removed isolated single pixels of snow, no-snow, or cloud by assigning to the pixel the majority value of its 4 nearest neighbors, if 3 or 4 of them were the same. Next, the value of "snow" or "no-snow" was interpolated across all single-day cloudy periods bounded on both sides by the same class. Then "snow" and "no-snow" classes were interpolated through longer cloudy periods, but the routine differed depending on the time of year. The snow class was interpolated back in time through cloudy periods in the winter and spring, while the no-snow class was interpolated forward in time through cloudy periods in the fall. The very first and last snow days (the "full snow season") in the snow year were then located. The algorithm also scanned for periods of continuous snow cover more than 2 weeks long with 2 or fewer days of no-snow. The start and end of the longest of these continuous snow periods were determined and the longest one was selected (the "continuous snow season", CSS). For more details of the algorithm used to derive the snow cover metrics, see Zhu and Lindsay (2013).

The following metrics from this processing were used in this report:

- First snow day – the first day of snow recorded in the snow year (i.e. after August 1). This day can be followed by snow free periods before the start of CSS (below).

- Last snow day – the last day of snow recorded prior to the end of the snow year (July 31). Snow-free periods can separate the last snow day from the end of CSS (below).
- Start of CSS – the first day (in the fall) of the longest continuous snow season
- End of CSS – the last day (in the spring) of the longest continuous snow season

Terrain shadows as a function of sun elevation above the horizon were computed using the ArcGIS "Hillshade" geoprocessing tool (http://resources.arcgis.com/en/help/main/10.2/index.html#//009z000000v0000000) assuming a sun azimuth of 157.5° (corresponding to 10:30 AM local time, the time of the MODIS satellite pass). The formulas for computing the sun's elevation above the horizon through the year were taken from NOAA (2013).

Data Analysis

The medians of all 13 years of data were computed for the four metrics analyze here (first snow day, last snow day, start of CSS, end of CSS) to represent the "normal" condition. The median was chosen over the mean, because the median is less affected by a few anomalous values than the mean. As discussed below and in the Results section, cloudiness combined with low sun angles caused the snow season algorithm to "miss" the establishment of snow cover in some areas in a few years, and thus assign anomalously late values for first snow day and start of CSS.

Remote sensing of the time of snow cover establishment is difficult at high latitudes due to low sun angles. At a latitude of 68° N (the latitude of central NOAT and GAAR, i.e. representative of the bulk of ARCN), the height of the sun is below the horizon at the time of the MODIS Terra's pass (10:30 AM local time) from about Nov 21 through Jan 20 (days 325 through 20 in Fig. 4). The sun is less than 5° above the horizon at 10:30 AM from about November 1 through February 8 (days 305 through 39) and below 10° from about Oct 17 through Feb 24 (days 290 through 55). Terrain shadows cover about 22% of ARCN when the sun angle is 5° above the horizon and 8% when the sun angle is 10°. Thus to obtain a start of snow season date, the snow cover must both become established and clear weather allow it to be observed in October or earlier in mountainous terrain and early November at the latest in the lowlands.

As a result of problems with detecting the start of snow season data for some years, I omitted analysis of year-to-year variation in start of snow season. Also, I calculated the length of the snow season (both the full snow season and the CSS) by subtracting the 13-year median for the start of the snow season from the 13-year median end of the snow season, rather than computing the length of the snow season for individual years.

The sun angle was much less of a problem in the spring. By late February sun angles are high enough to minimize terrain shadows (e.g., 10° on day 55 in Fig. 4), and clear weather is more frequent in the spring than the fall. Thus I was able to analyze year-to-year variation in spring date of snow cover loss. In any given year large areas were "early" or "late" relative to the long-term median by approximately the same amount; thus the difference between individual years and the 13-year median was averaged over zones of interest (e.g. NPS unit) to summarize year-to-year variations in spring date of snow loss.

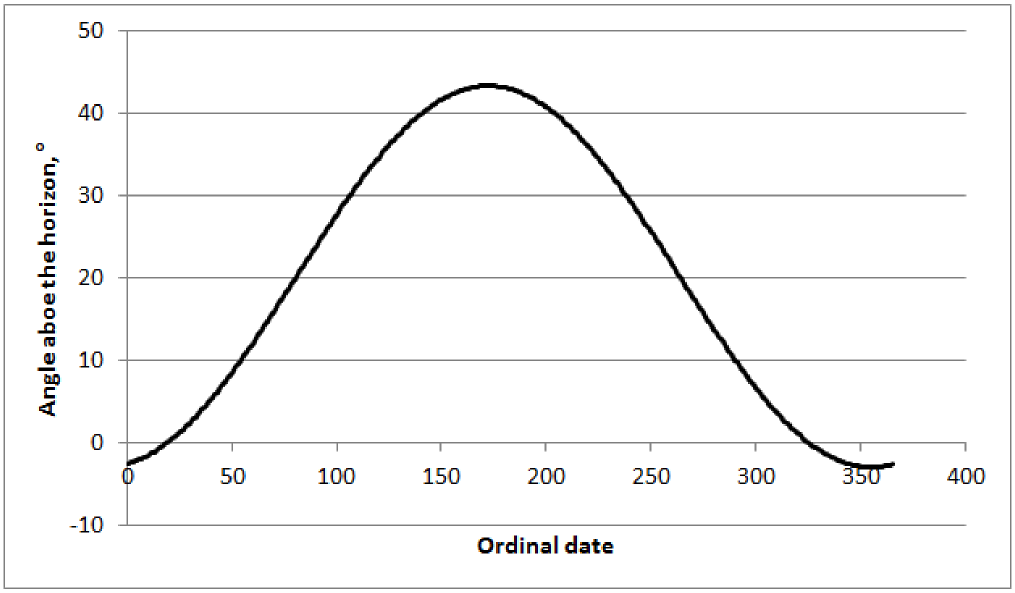

Figure 4. Plot of sun angle above the horizon vs. date for 10:30 AM local time at 68° north latitude (NOAA 2013).

To test for long-term trends in the timing of snow cover loss, least-squares linear regressions were computed for last snow day vs. year and end of CSS vs. year for each individual pixel, and tested for significance with a t-test (Snedecor and Cochrane 1989).

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Results and Discussion

Establishment of Snow Cover in the Fall

The median first snow day was in October over most of the low-elevation areas (<2000 feet, 620 m) of ARCN, and mainly in September at elevations above 2000 feet (620 m)(Table 1, Fig. 5). However, the first snow typically came in August at high elevations (above 3000 feet, 914 m) on the north side of the Brooks Range in GAAR. The start of the continuous snow season (CSS) was within 2 weeks of the first snow day over most of ARCN: late October in the lowlands (<1000 feet, 305 m) of western ARCN and early October elsewhere, except at high elevations (>3000 feet, 914 m, mainly in GAAR), where the CSS began in September (Fig. 6).

Table 1. Snow Metrics in ARCN Summarized by Elevation

	Mean (Standard Deviation) Date[1] by elevation					
Snow Season Metric	**0-305 m 0-1000 ft**	**305-620 m 1000-2000 ft**	**620-914 m 2000-3000 ft**	**914-1219 m 3000-4000 ft**	**1219-1524 m 4000-5000 ft**	**>1524 m >5000 ft**
Median first snow day	283 (16)	276 (10)	271 (7)	265 (8)	258 (9)	249 (10)
Median start of CSS	291 (19)	283 (9)	277 (5)	272 (5)	267 (5)	261 (7)
Median last snow day	137 (24)	141 (15)	141 (8)	144 (8)	148 (9)	155 (10)
Median end of CSS	135 (30)	139 (16)	138 (8)	139 (8)	142 (10)	145 (11)
Median length of full snow season, days	219 (16)	230 (12)	235 (12)	243 (13)	255 (15)	271 (17)
Median length of CSS, days	209 (17)	221 (12)	226 (11)	232 (10)	240 (13)	249 (16)

[1]Ordinal date; for conversion to month and day, see Table 2.

Table 2. Ordinal Dates of the First and Fifteenth Days of the Month

Month	**Ordinal Date of the: 1st**	**15th**
May	121	135
Jun	152	166
Jul	182	196
Aug	213	227
Sep	244	258
Oct	274	288
Nov	305	319

The short time interval between the first snow day and start of CSS across all of ARCN demonstrates that the transitional period of ephemeral snow cover is quite brief, and winter arrives quickly. The earlier establishment of snow cover at high elevations is not surprising, but there was also an east-west trend independent of elevation: the start of CSS was in early October at low elevations in southern GAAR, while low elevations further west acquired their continuous snow cover in late October (Fig. 6). This is probably a maritime climatic effect, as shown by the earlier arrival of subfreezing daily mean temperatures at the Noatak RAWS than Kotzebue (Fig. 2). Both the first snow day and start of CSS were earlier in the mountains north of the continental divide in GAAR than at similar elevations in southern GAAR. Apparently arctic air masses bring snow to the northern mountains early in the season, while the warmer conditions persist a little longer on the south slope.

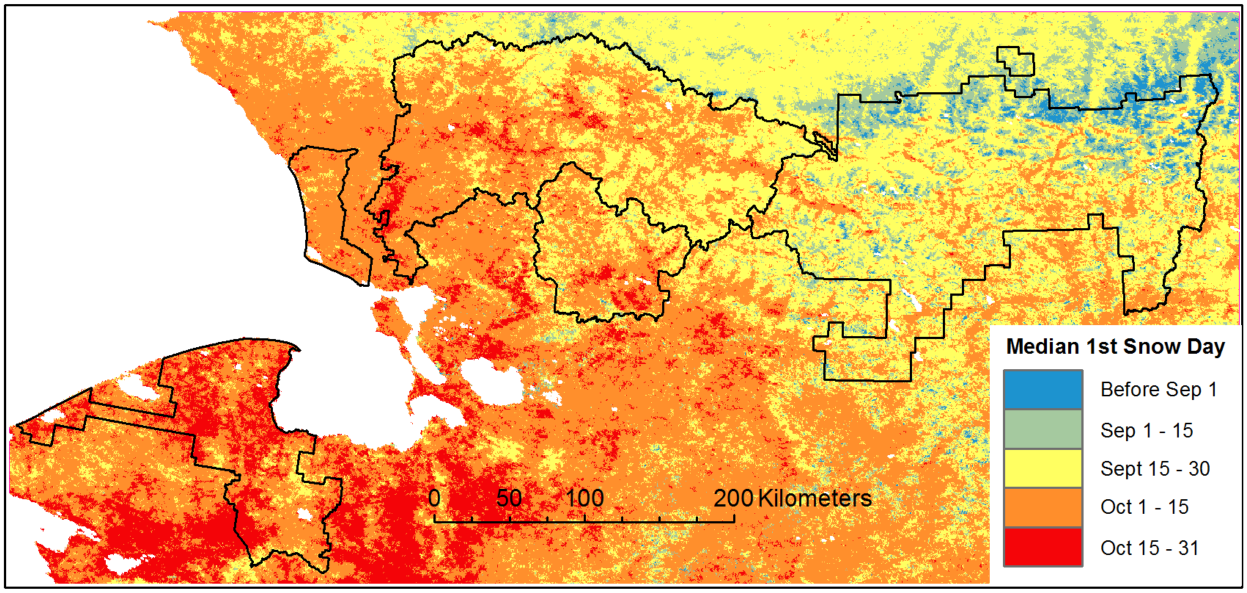


Figure 5. Median first snow day for the years 2000-2012.

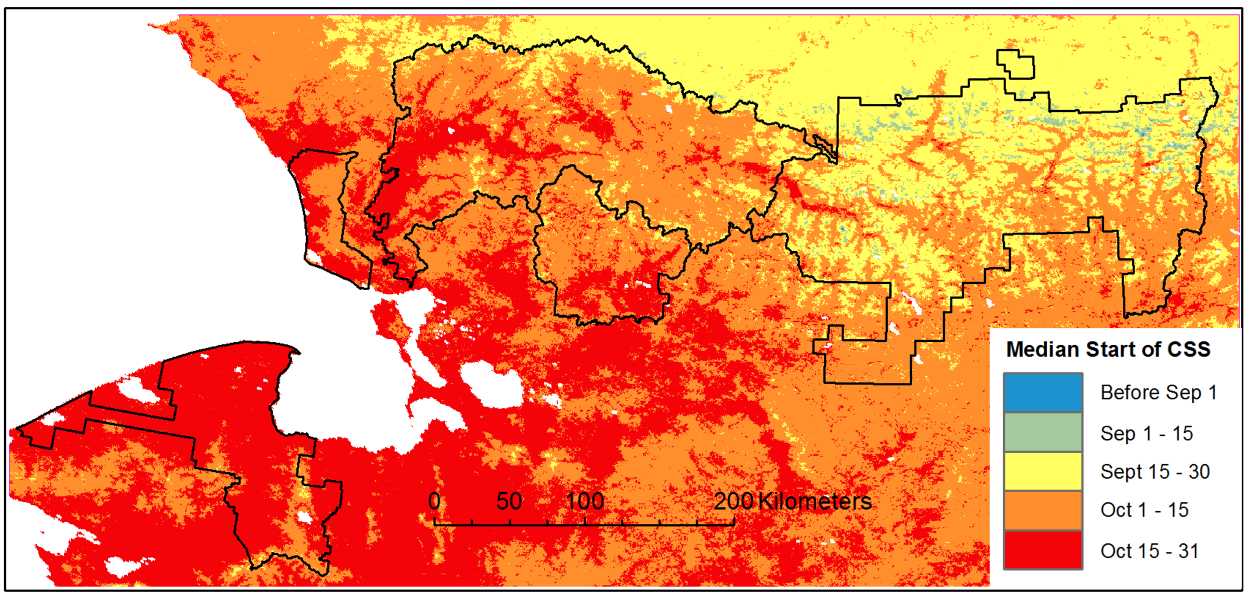


Figure 6. Median start of continuous snow season (CSS) for years 2000-2012.

While the data for median first snow day and the start of CSS appear reasonable, examination of snow establishment dates for individual years revealed some years with numerous pixels coded for dates after November 1 that must be considered suspect. Particularly suspicious are snow establishment dates of "365" (December 31), which is the default assigned when the algorithm fails to find snow cover in the fall. For example, for NOAT in the year 2010, 28% of all pixels had a start of CSS of Nov 1 (the first date when the sun angle at the time of the satellite's pass is below 5°) or later, including 7% on Dec 31, when the sun never rises.

The effect of these uncertainties and probable errors in snow establishment dates on the median first snow day and median start of CSS values (Figs. 5 and 6) appear to be minimal, probably for the following reasons. Errors should occur mainly in years with late snow cover arrival, and the effect is to cause the first snow date and start of CSS to be recorded as later than they actually were. As long as errors of this type occur on a given pixel in fewer than half of the years, the median is unaffected. Inspection of the data indicate that in any given area there were only 3 or 4 problem years out of the 13 available.

Loss of Snow cover in the Spring

Median end of snow season

The median last snow day and median last day of the CSS are less than a week apart in May over most of ARCN (Table 1, Figs. 7-9). A zone with larger difference between the median last day of the CSS and median last snow day (over 2 weeks and as much as a month in places) stretches across the northern foothills of GAAR. Thus in ARCN late snowstorms typically do not re-establish a snow cover after the main winter snowpack is lost in the spring, except in the foothills of northern GAAR.

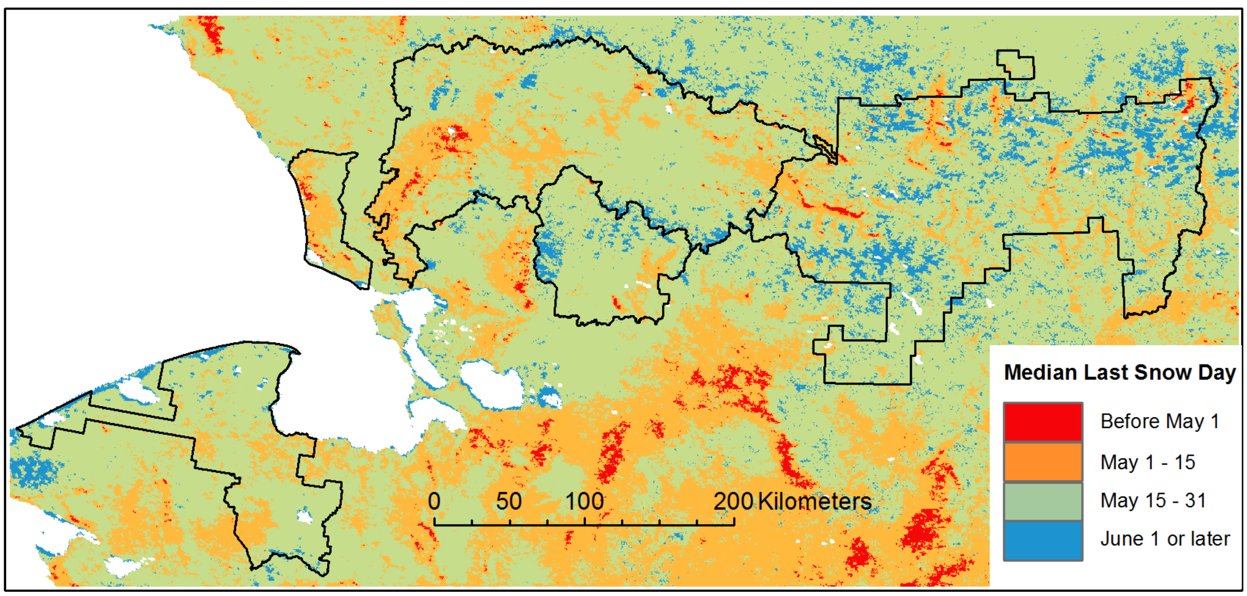


Figure 7. Median last snow day for years 2001-2013.

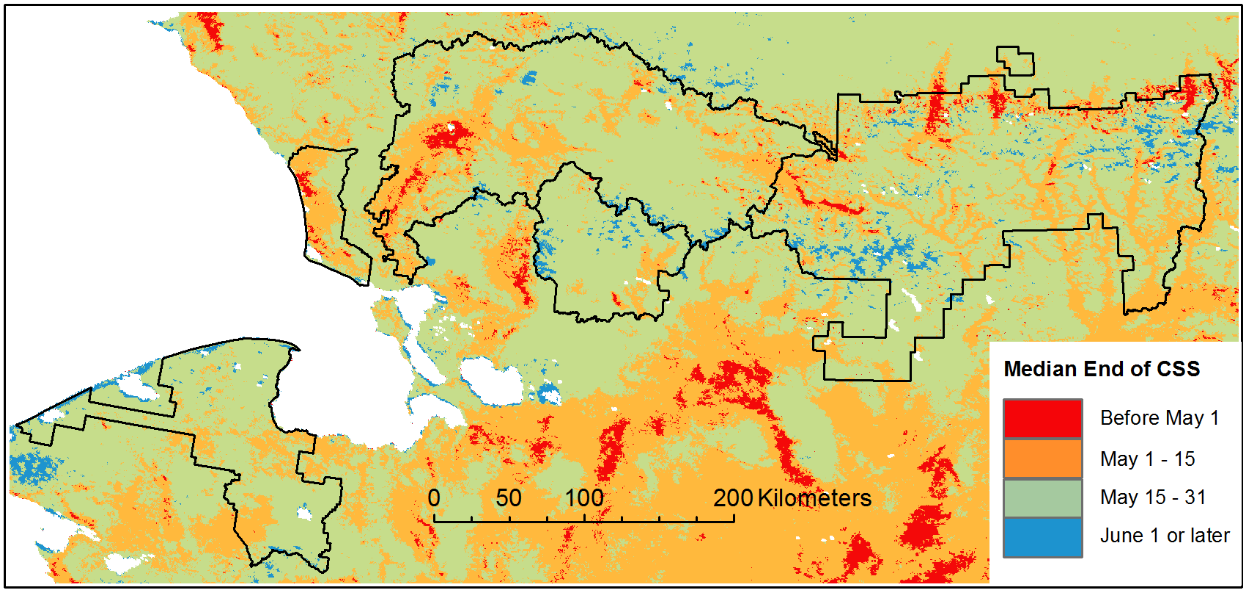


Figure 8. Median end of CSS for years 2001-2013.

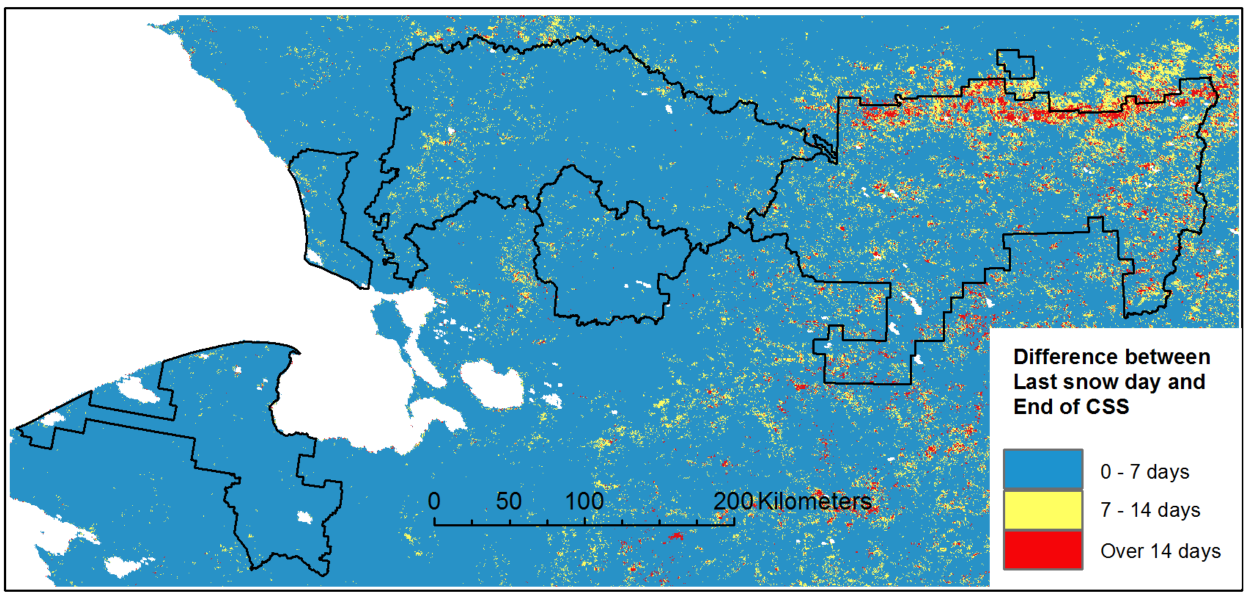


Figure 9. Difference in days between the median last snow day and the median end of the CSS.

The spatial patterns in median end of CSS and last snow day derived here from MODIS data are strikingly similar to those obtained by Macander and Swingley (2012) from analysis of Landsat data for the period 1985-2011 (Fig. 10). They used a classification tree analysis to choose the best date that separated snow-covered and snow-free dates for each pixel. Since 91% of the Landsat scenes available for Macander and Swingley's analysis were from 2000-2011, our two study periods nearly coincide. The higher resolution of the Landsat data is apparent, while the overall agreement from these two entirely independent analyses gives us confidence in both. Note that due to the infrequent passes of the Landsat satellite (16 days), the full period of record was required to compute the end of snow season dates in Fig. 11, and further analysis of trends or year-to-year variability (as we do below with MODIS data) was not possible.

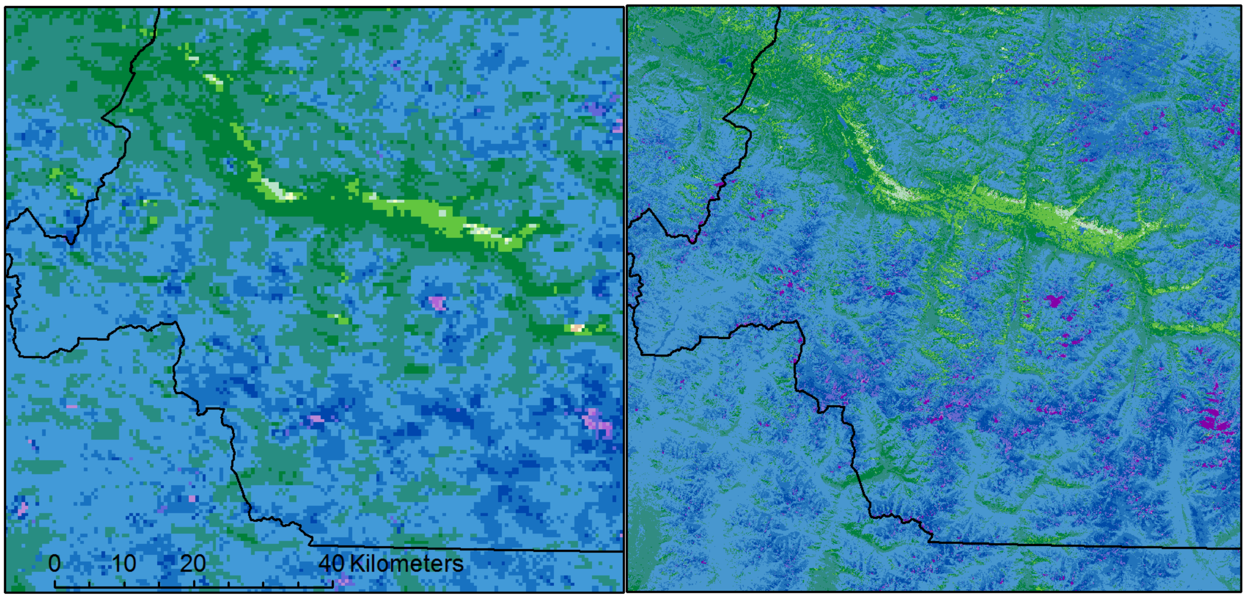


Figure 10. Comparison of end of snow season maps obtained from MODIS (left, 500 m resolution, this report) and Landsat (right, 30 m resolution; Macander and Swingley 2012). The area covered is southwestern GAAR (border in black): the upper Noatak River valley and Schwatka Mountains. The MODIS map is median last snow day (2001-2013); the Landsat map is the end of snow season obtained using a binary classification tree approach to separate snow-covered and snow-free dates on all Landsat images available 1985-2011, with the bulk of available scenes from 2000-2011. Dates on the map range from mid-April (light green) to July (violet).

Higher elevations in ARCN generally had later snow-off dates, though there was some interesting variability within this overall pattern. Snow disappeared in April and early May in valleys on the north side of the Brooks Range in GAAR, parts of the Noatak Valley, and the hills that face the Chukchi Sea in CAKR (Figs. 7-9). These early snow-loss zones are identified on Fig. 11, and example photographs from the Itkillik Valley are given in Fig. 12. Snow-off dates in these locations are earlier than many places at lower elevations and further south in the Kobuk Valley of southern GAAR and KOVA. There is also a small spot of April snow cover loss in KOVA that coincides with the Great Kobuk Sand Dunes. These anomalous early snow-off areas probably have thin snow covers as a result of both high winds and relatively low snow precipitation (note the estimated winter precipitation values for these locations in Fig. 3). Microclimates with high solar radiation also play a role, especially in some interior valleys: note the band of April snow-off visible on the north side (i.e. south-facing slopes) of the upper Noatak Valley (Fig. 10).

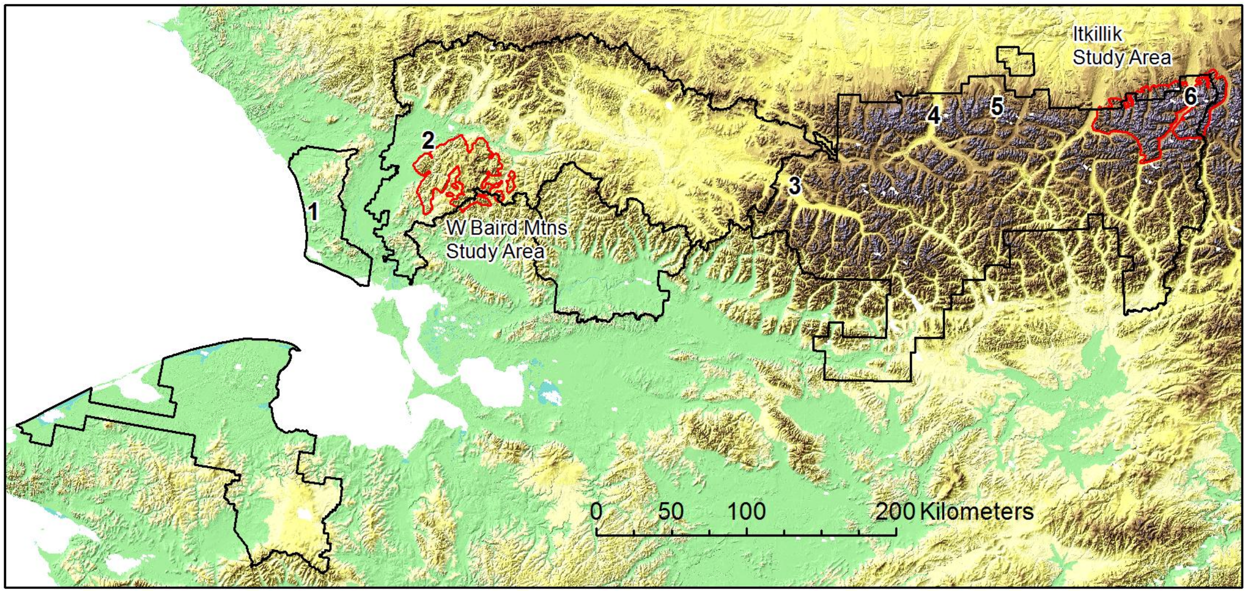


Figure 11. Zones of early snow cover loss and sheep study areas. Numbers label notable zones of early snow cover loss: 1) Chukchi Sea coastal mountains, 2) Western foothills of the Baird Mountains and adjacent lowlands near the lower Noatak River, 3) upper Noatak River valley, 4) Killik River valley, 5) Okokmilaga River valley, and 6) Itkillik River valley.

Some interesting areas of late snow cover persistence, probably reflecting especially deep snowpacks, are also apparent. The most curious is the Kallarichuk Hills in western KOVA (see the areas in western KOVA coded as "June 1 or later" in Figs. 7 and 8). These hills are not particularly high (mostly under 3000 feet or 915 m), and they form a southern projection of the Baird Mountains into the Kobuk Valley. The western slope of the Kallarichuk Hills (just outside of KOVA to the west) appears to be extremely windswept, judging from its early snow-off dates, while the snow at similar elevations on the eastern side of the hills persists into June down to elevations below 1000 feet (305 m). The implication is that snow is deflated from the east slope of the Kallarichuk Hills and deposited to form deep snowdrifts on the east slope. However, this hypothesis is apparently contradicted by wind data for nearby weather stations (e.g., the Kiana RAWS http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?akAKIA), which show predominant winter winds out of the east.

Orographically enhanced snowfall that occurs as moist air masses from the southwest encounter the south slope of the Brooks Range is apparent in the late snow-off dates in northeastern KOVA, southeastern NOAT, and southwestern GAAR (Fig. 8; see also winter precipitation values in Fig. 3). The persistent snow areas in northern GAAR coincide with the largest concentration of high elevation terrain (e.g. over 5000 feet, 1524 m) in ARCN.

Figure 12. The Itkillik River Valley in late winter. The is an area that typically loses its snow cover early due to wind and relatively light precipitation (see Fig. 11, point 6 and Figs. 8-9). In a typical year (Fig. 8), the end of the CSS here is in April here on both the valley floor and adjacent slopes. The upper photo (18 April 2012) was taken in a year when the CSS ended in early May on the valley floor and April on most adjacent slopes; this was a week or two later than normal for the area. The lower photo (17 April 2013) was taken in a year when the CSS ended in May on the valley floor and adjacent slopes,i.e. about a month later than normal. Photo locations were near latitude 68.23°, longitude -150.12°. Photos by Zak Richter (upper) and Heidi Kristenson (lower).

Long-term trend in end of snow season

Linear regressions for the end of CSS vs. year and the last snow day vs. year for individual pixels showed no significant correlation for the vast majority of pixels in ARCN. A two-tailed significance test for a correlation coefficient with n = 13 would indicate significance at the 10% level for any correlation coefficient greater than 0.476 or less than -0.476 (Table A10 in Snedecor and Cochrane 1989). Less than 1% of the approximately 327,500 MODIS pixels in ARCN had correlation coefficients outside of this range for either regression. This is actually *less* than what we would expect by chance (i.e. in such a large set of regressions, one would expect about 10% of the coefficients to fall outside the 90% confidence limits by chance alone). While the overall trend over the past century in North America has been toward earlier snow-cover loss due to climate warming (Brown and Robinson 2011), our observed lack of a warming-related trend in the period 2001-2013 is consistent with climate observations showing that most of Alaska experienced a slight cooling in the 2000-2010 decade, especially in the winter, as a result of a shift in the Pacific Decadal Oscillation (Wendler et al. 2012). It also illustrates that, as a result of large inter-annual variations, we will need a long time series to understand temporal trends in snow cover loss.

Year-to year variation in end of snow season

The standard deviation of the end of snow season date gives us a picture of the variability in time of snowmelt (Fig. 13). Over most of ARCN the standard deviation in end of CSS was 14 days or less, which means that the snow disappeared within the same 1-month period in at least 2 out of 3 years. The greatest variability occurred on slopes along the northern edge of the Brooks Range in GAAR, where the standard deviation was greater than 14 days, and snow-off dates have ranged from February to May during the study time interval. These areas are apparently completely windswept in some years (hence the February end of CSS dates, which may in fact mark emergence from winter shadow), while in other years enough snow accumulates to register as “snow covered” until the spring thaw in May.

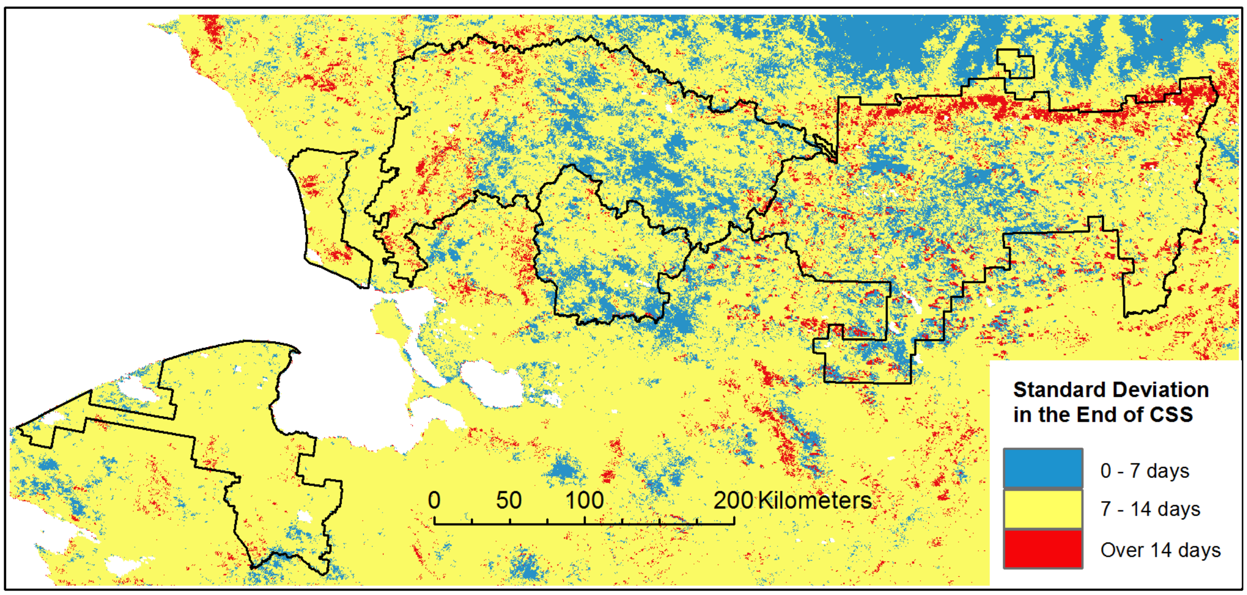


Figure 13. Standard deviation in the end of CSS, 2001-2013.

The years with the most extreme deviation in end of CSS were 2001 (late snow persistence) and 2004 (early snow cover loss; Figs. 14 and 15). In 2001 the end of CSS was more than a week later than the median over most of ARCN and over 2 weeks late in the west; snow persisted into June in many lowland areas as well as in the mountains. However, the valleys that typically lose their snow cover early (described previously, see Figs. 8 and 11) had fairly typical snow-off dates in 2001. A somewhat similar situation occurred in 2003, except in the western units (CAKR and BELA), where snow-off was early. In 2004, snowmelt occurred over 3 weeks early in the west (April), while most of GAAR was about a week earlier than normal. In 2002, 2006, 2008, and 2011 the end of CSS was fairly close to the median across most of ARCN. In 2005, 2007, 2009, 2010, 2012, and 2013 there was a mix of local areas with early and late end of CSS. The spring of 2013 was unusually late over much of Alaska, but the end of CSS in ARCN was not uniformly late: the end of CSS was late in the northern Brooks Range foothills GAAR (see Fig. 12), in CAKR, and in parts of western NOAT, but actually a bit early in north-central NOAT.

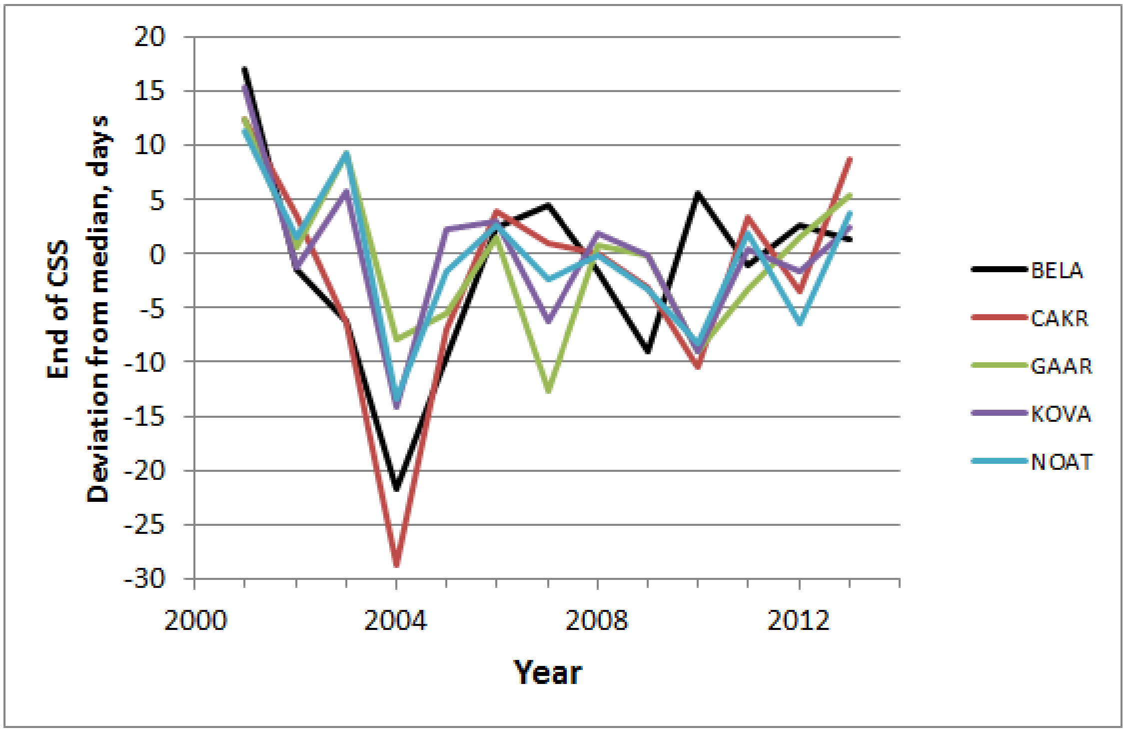


Figure 14. Mean deviation from the typical (median) end of CSS by NPS unit by year.

In general, the year-to-year variation is similar in the three contiguous, inland parks (GAAR, NOAT, and KOVA), while the two westernmost, coastal parks (CAKR and BELA) sometimes do not match the other three (Fig. 14).

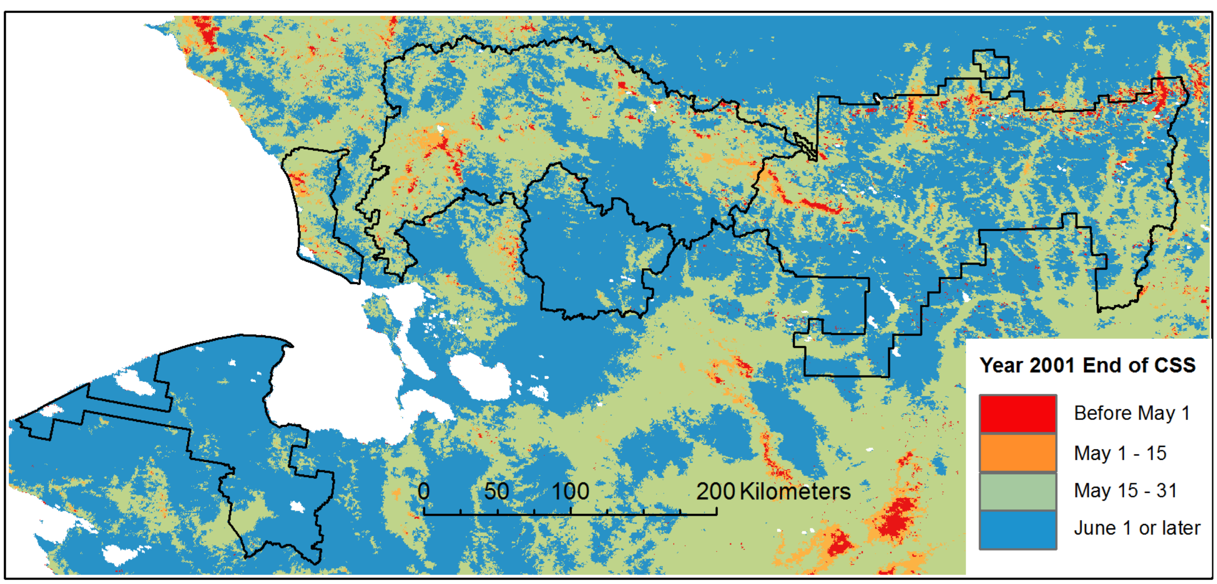
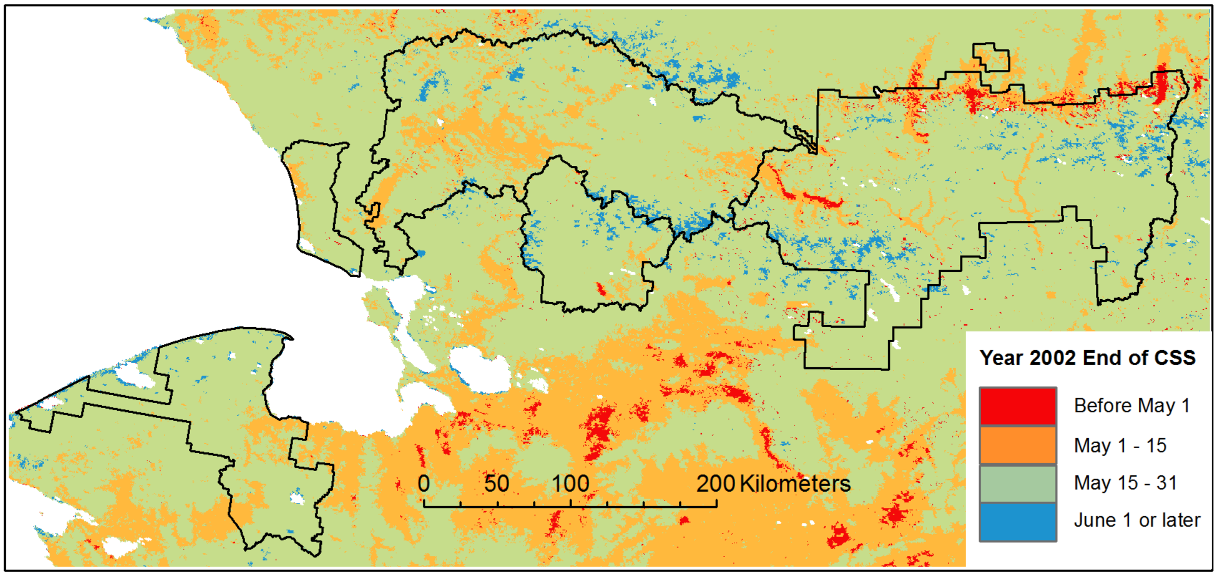
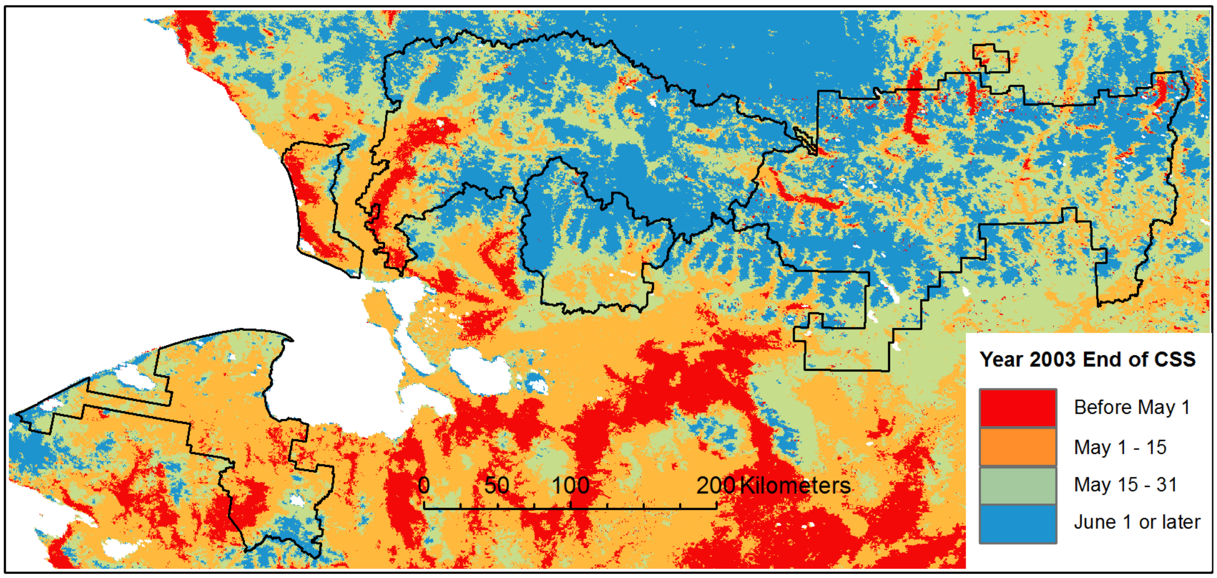
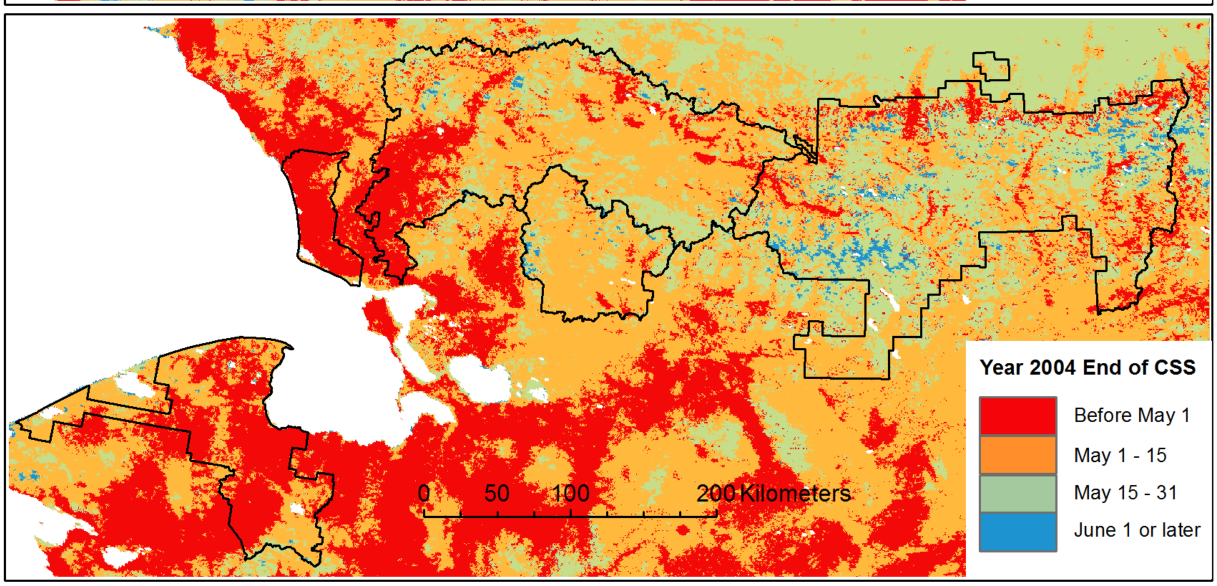
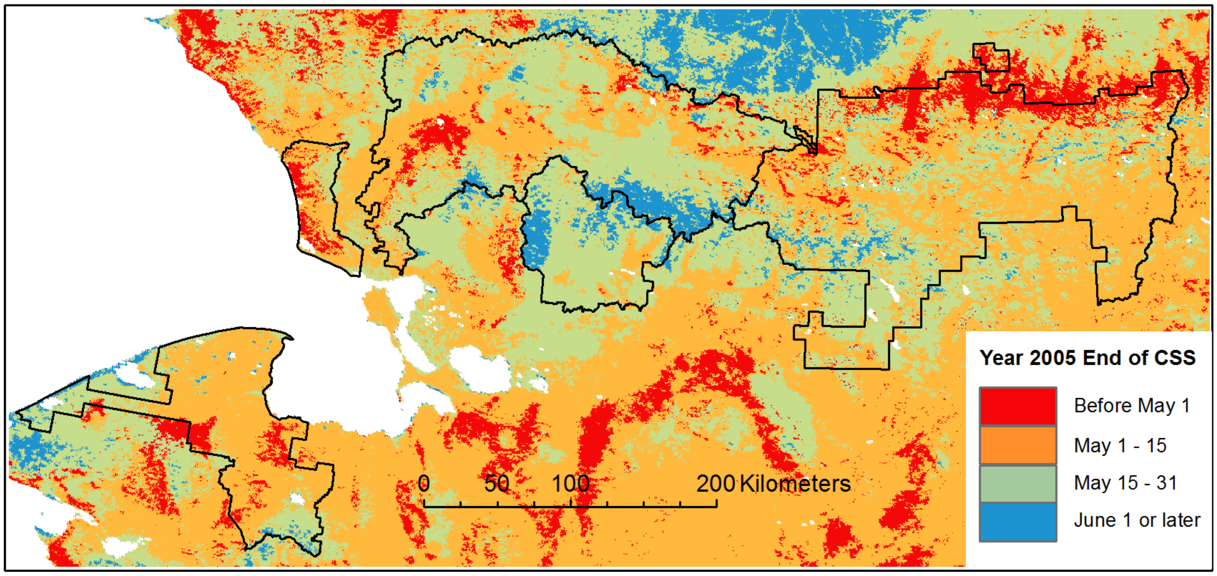


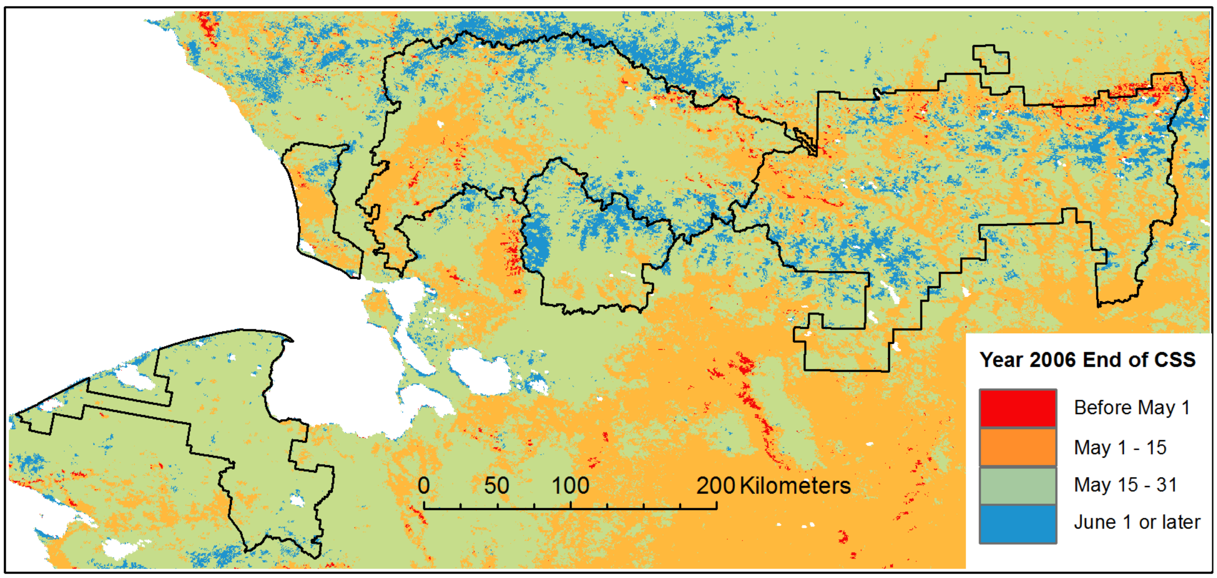
Figure 15 (here and following 4 pages). End of CSS in ARCN, years 2001 through 2013.

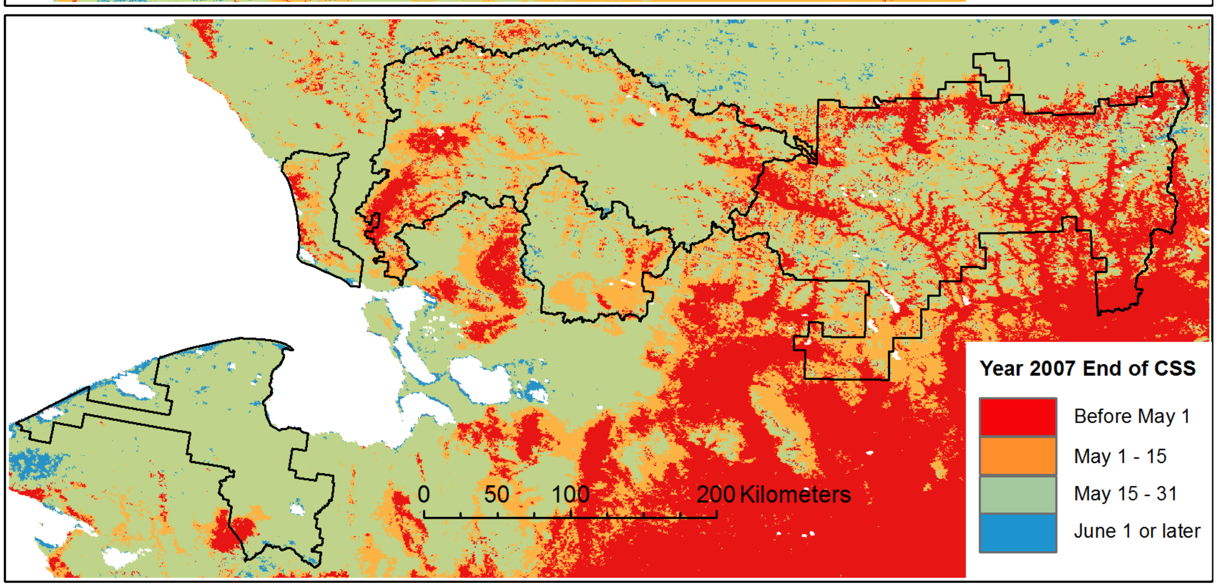

Year 2002 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers

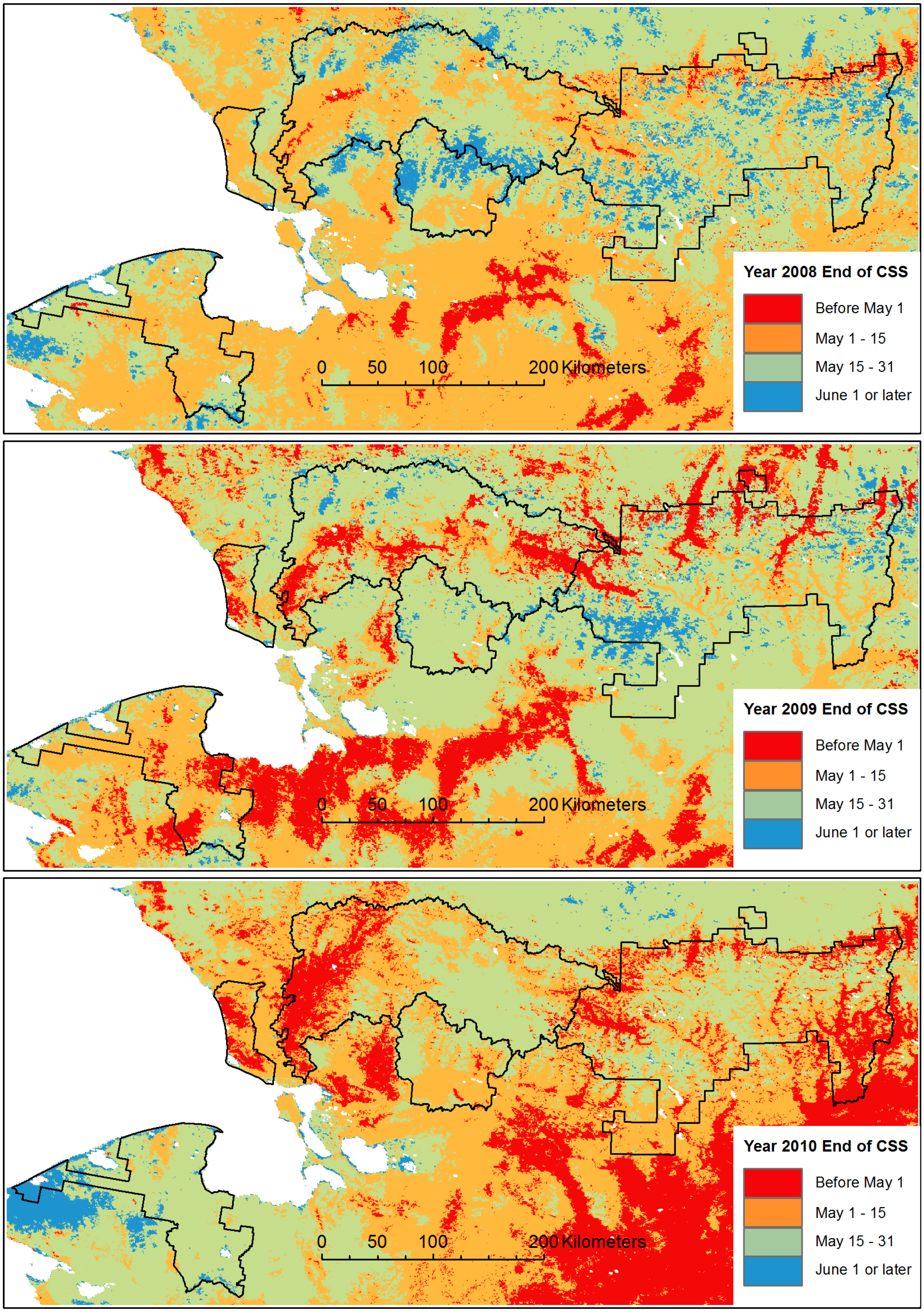

Year 2003 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers

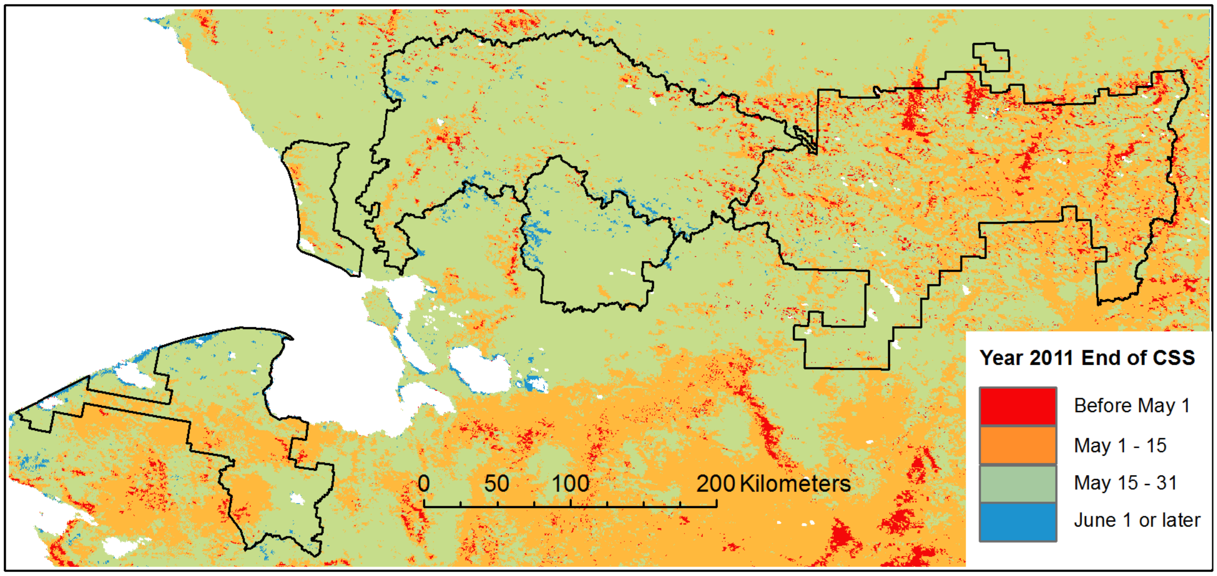

Year 2004 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers

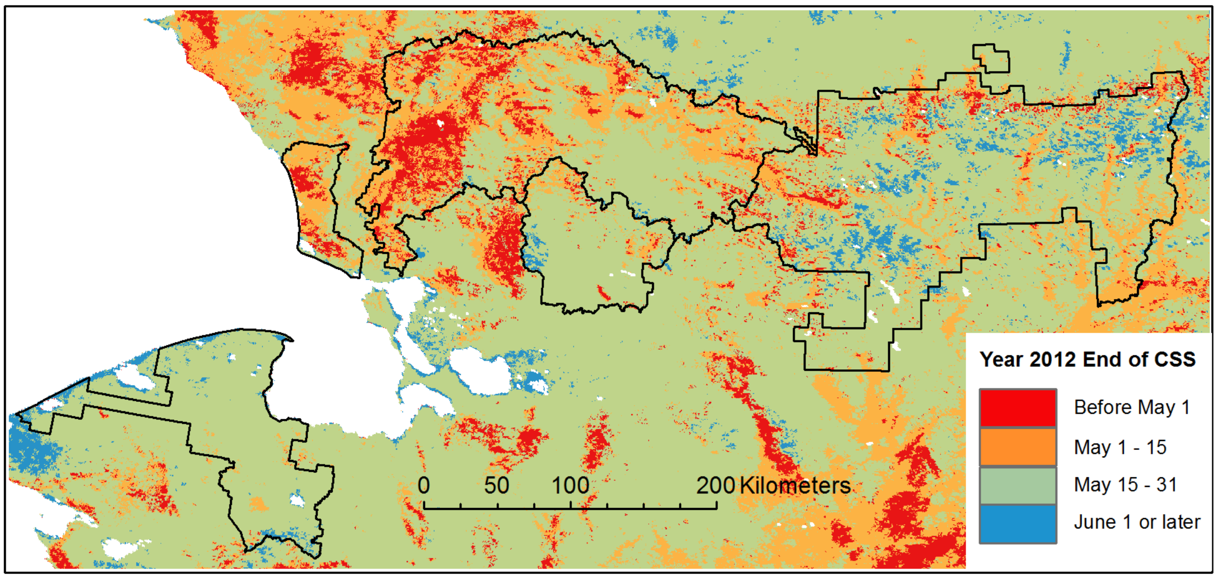

Year 2005 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers

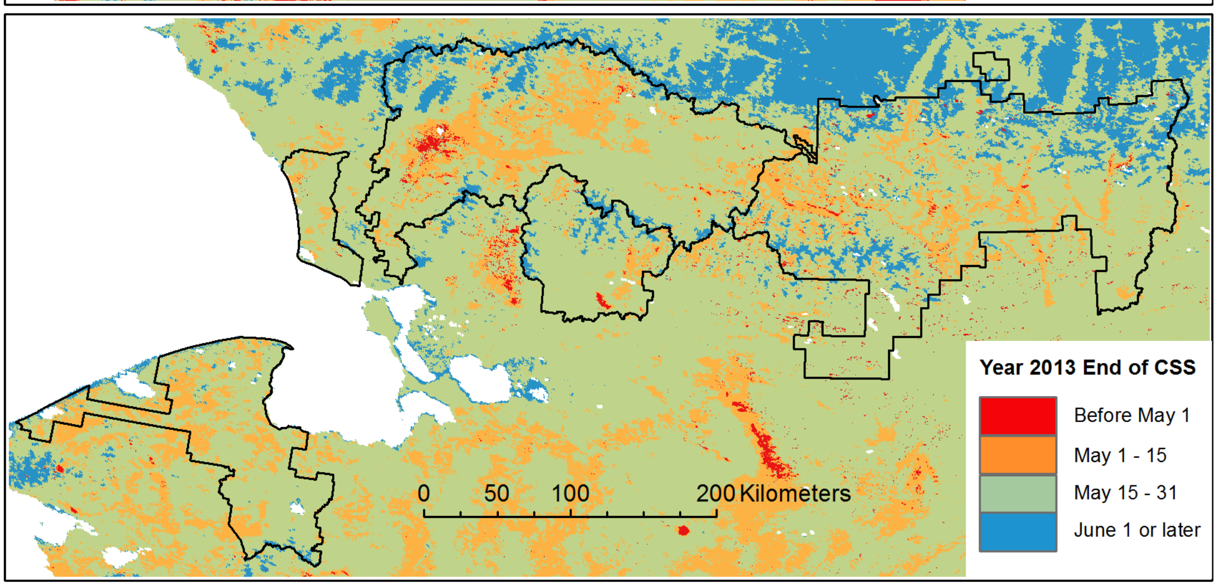

Year 2006 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers


Year 2007 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers


Year 2008 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0
50
100
200 Kilometers
Year 2009 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0
50
100
200 Kilometers
Year 2010 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0
50
100
200 Kilometers


Year 2011 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers


Year 2012 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers


Year 2013 End of CSS
Before May 1
May 1 - 15
May 15 - 31
June 1 or later
0 50 100 200 Kilometers

The end of the snow season is related to the occurrence of wildfires in the following summer. During the study period, the years with most area burned in ARCN were 2010 and 2012. Most of the area burned was in NOAT, and the fires were caused by lightning and started in June or very early July (AICC 2014). The summer of 2004 was a big fire year for many parts of Alaska, though not in ARCN. Years with an early end of CSS for NOAT were 2004, 2010, and 2012 (Fig. 14). Early loss of snow cover was probably a factor in the fires in these years, because it allowed the fuels to dry out before the onset of the cool wet weather that is typical of late summer.

The end of CSS can be used as an indicator of winter severity for wildlife, because a late end of CSS represents some combination of deep snow and late onset of spring warming. The difference between individual years' end of CSS and the long-term median was averaged over the sheep population study areas of Schmidt and Rattenbury (2013); their study-area boundaries are shown in Fig. 11. The western Baird Mountains study area followed the trends for NOAT quite closely (compare Figs 16 and 14). The Itkillik study area (Fig. 16) had a pattern similar to the larger park unit (GAAR, Fig. 15) but with greater variability: the end of CSS was over two weeks late in 2003 and 2013 and nearly three weeks early in 2007, while for GAAR as a whole the average deviation was less than 2 weeks throughout the study period.

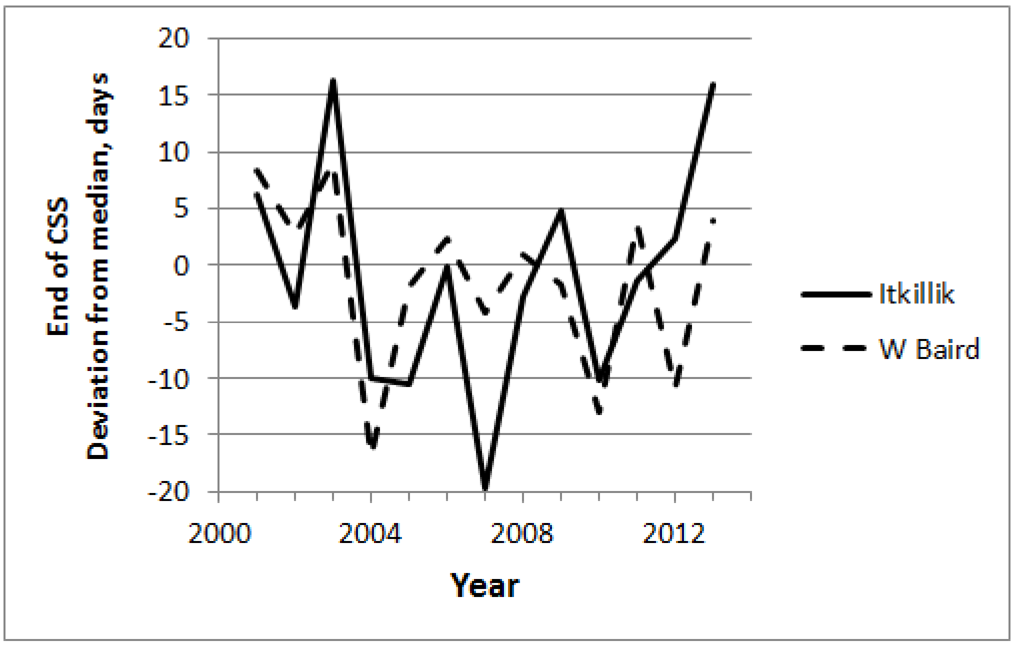


Figure 16. Average deviation from the 2001-2013 median end of CSS for ARCN sheep population study areas: the Itkillik River valley (GAAR) and the western Baird Mountains (NOAT; Schmidt and Rattenbury 2013). See Fig. 12 for the study area locations.

Length of Snow Season

The length of the full snow season (the difference between the first and last snow days) was between 6 and 7 months (183 to 213 days) in some lowland areas (<1000 feet, 305 m, mainly in the west) and over 274 days (more than 9 months) in the highlands of GAAR above 5000 feet (1524 m; Table 1, Fig. 17). The length of the continuous snow season (Table 1, Fig. 18) was just under 6 months (183 days) in a few places (the largest was in the western Noatak Valley), 6 to 7 months (183-213 days) in many lowland areas (below 1000 feet, 305 m), 7 to 8 months (213 to 243 days) at most mid-elevations, 8 to 9 months (243-274 days) at high elevations (above 4000 feet, 1219 m), and over 9 months (274 days) on just a few north-facing slopes at high elevation.

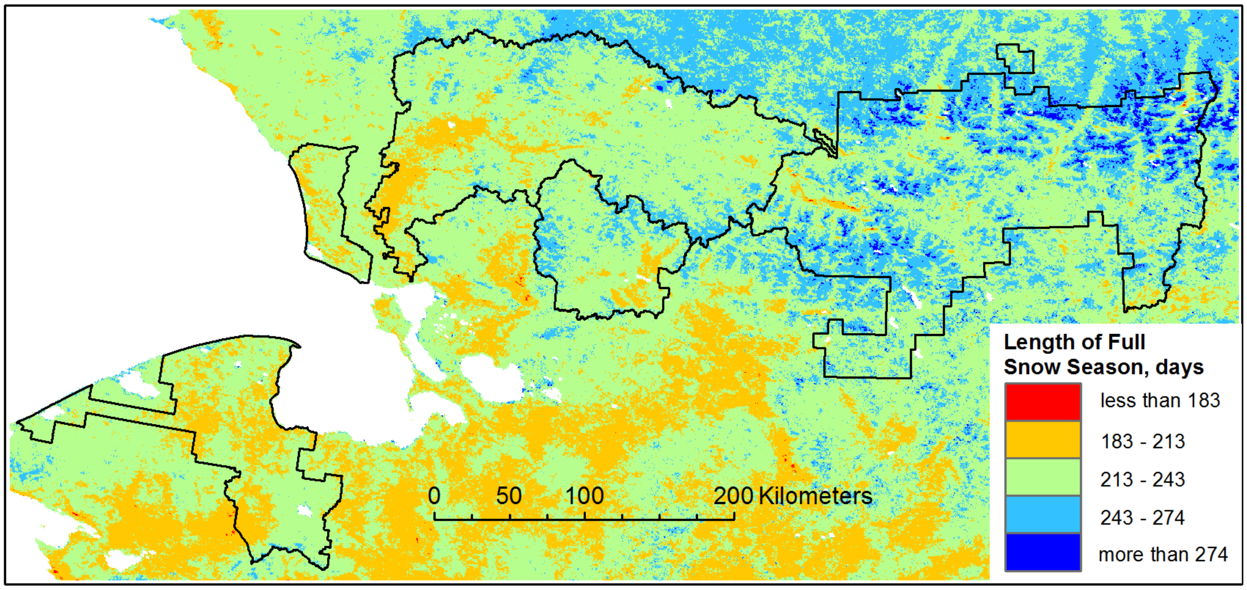


Figure 17. Median length of the full snow season in ARCN. The full snow season is the difference between the median last day (Fig. 8) and median first day with snow (Fig. 5). The day ranges are < 6 months (<183 days), 6 to 7 months (183 to 213 days), 7 to 8 months (213 to 243 days), 8 to 9 months (243 to 274 days), and more than 9 months (>274 days).

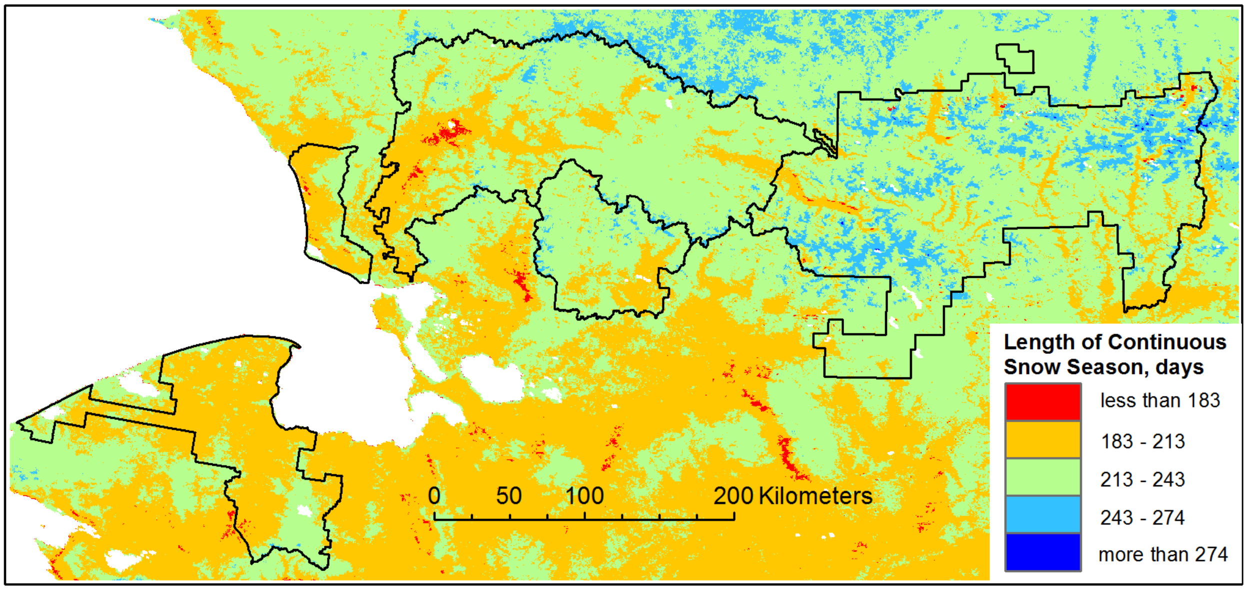


Figure 18. Median length of the continuous snow season (CSS) in ARCN. The length of CSS is the difference between the median last day of the CSS (Fig. 9) and median first day of the CSS (Fig. 6). The day ranges are < 6 months (<183 days), 6 to 7 months (183 to 213 days), 7 to 8 months (213 to 243 days), 8 to 9 months (243 to 274 days), and more than 9 months (>274 days)..

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